Teaching Sustainable Design through Simultaneous Evaluation of Economics and Environmental Impacts

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Abstract

The ever-increasing human population and industrial growth have posed a considerable burden on existing resources and have led to an increase in environmental pollution and climate change. The Engineering Clinics offered at the Henry M. Rowan College of Engineering at Rowan University is the hallmark of our program that enables our undergraduate students to actively participate in solving real-world problems through collaborative activities. Our graduate students get an opportunity to engage in stakeholder (*i.e.*, industries, federal and regional funding agencies) interactions and student mentoring in conjunction with developing their research ability. Thus, through these synergistic undergraduate-graduate-faculty-stakeholder collaborations this work envisions to develop awareness about sustainable design and environmental impact in the community. The clinic problems include; (i) solvent recovery in process industries, and (ii) systematic synthesis of wastewater treatment (WWT) networks. These problems are important because imprudent use of industrial solvents and water resources have exacerbated the challenges relating to availability, quality as well as safe disposal of harmful solvents and wastewater. Through these challenging and relevant problems, we can teach our students multiple skills such as information collection, selective extraction of valuable content, economic and sustainability evaluation of multiple pathways through mathematical modeling, computer programming, technical writing, and presentation. The overall impact of these efforts is evident in the peer-reviewed conference and journal publications, oral and poster presentations at regional and national conferences, as well as our students choosing careers which value sustainability.

1 Introduction

The unique feature of the undergraduate curriculum at the Henry M. Rowan College of Engineering (HMRCOE) at Rowan University (RU) is the Engineering Clinics, which are offered in conjunction with all the required courses every semester. The undergraduate students from all the engineering disciplines are part of a common clinic activity in their first two years, which are aimed at enhancing the basic engineering skills and to increase an aptitude for reason-based learning. They also learn basic technical writing and presentation skills in these two years. In their junior (3rd) and senior (4th) years, these students get an opportunity to participate in discipline-specific research-based clinics where they have an opportunity to engage with stakeholders from industries and federal agencies and work on real-world problems. In this paper, we have placed an emphasis on one specific clinic project: solvent recovery in process industries. This project is offered in the Chemical Engineering department at RU to teach our students the importance of sustainable design and the impacts of chemical processes and their effluents on the environment. In the following sub-sections, the background and motivation in choosing this clinic project are emphasized.

1.1 Solvent Recovery and Reuse

The demand for solvents has expanded across many industries such as the pharmaceutical, adhesives, food, cosmetics, cleaning, and personal care industries. Solvents are typically used as dissolution medium, materials to aid in reaction, mass separation, and cleaning operations (Slater et al., 2010; Wypych, 2014). However, there are inefficiencies in the existing industrial manufacturing processes, which can be caused by large-scale production challenges such as inefficient mixing, insufficient reaction time, inappropriate technologies, quality of raw materials, measurement control anomalies, etc. (Cavanagh et al., 2014a; Raymond et al., 2010). The global chemical market is projected to double between 2017 and 2030. However, waste generation due to poor solvent selection and processing inefficiencies in the chemical industry have led to a growing concern for chemical releases, exposures, environmental impacts, and health safety (United Nations Environment Programme, 2019). The US EPA has estimated that solvent emissions resulting from the chemical market growth can reach up to 10 million metric tons of carbon dioxide equivalent (US EPA, 2016, p. 2).

1.2 Role of Process Systems Engineering (PSE)

The selection of appropriate solvent recovery technologies is a function of the physicochemical properties of solvents, other components present in the waste stream, and the desired final purity levels to be achieved after separation. These separation technology options may include sedimentation, filtration, precipitation, distillation, liquid-liquid extraction, and pervaporation (Chea et al., 2019). Hence, this problem belongs to the process systems engineering (PSE) area, which comprises multiple methods and their associated computational tools to systematically solve the problem of generation of solvent recovery framework.

Furthermore, the availability of multiple recovery technologies, such as distillation, pervaporation, and aqueous two-phase extraction, adds complexity to the selection process A comparative assessment of the solvent recovery methods to the existing waste handling methods such as incineration is crucial to change the mindset of the people working in process industries as well as our undergraduates, who are the future workforce of the nation. Through PSE tools, we can selectively choose appropriate materials/methods for the efficient design of treatment systems and their sustainability over the desired period. Through planned projects, educational activities, and result dissemination, we aim to create an appreciation for ‘Sustainable Design in Engineering’ and motivate students to pursue it as their career path.

2 Methodology

2.1 Project Teams & Management

The clinic project team is composed of 2-3 undergraduate students, a graduate student mentor, and faculty advisors. The faculty develops contact with industries and other universities, applies for research and educational grants to federal and regional agencies, and private funding organizations. The faculty is responsible for developing the project goals and learning objectives for the students. The graduate student mentor is responsible for ensuring the project continuity, documentation, and partial supervision of undergraduate students. The engineering clinic is a 2-credit course every semester with biweekly meeting slots of 3 hours each. This course provides ample time for required student training, progress assessment as well as consultations with industrial liaisons and collaborators.

2.2 Tutorials for Basic Research Skills

As faculties, we provide students initial training on the necessary research tools and resources. The most crucial aspect for both these clinic projects was a literature review to collect relevant information about existing industrial processes and their waste streams, characterization metrics, existing case studies, technology information, and modelling. To this end, the students were trained to use literature review resources such as Google Scholar, and SciFinder Scholar. Instructions were provided on reading research papers effectively as well as categorizing them into reviews, model information, case studies, optimization, and simulations. Furthermore, they were trained to use citation managers such as Zotero and Mendeley to create a systematic database of references and cite them in research reports and manuscripts.

The next set of tutorials included training in PSE tools for mathematical modelling and optimization. Since both, the clinic projects involve a selection decision between multiple waste treatment and resource recovery technologies to meet the cost criteria and minimization of overall environmental impacts, the optimization tools needed were non-linear programming as well as discrete programming (Biegler et al., 1997; Diwekar, 2013). The theory, as well as software training in Matlab, GAMS, and P-graph (Heckl, Friedler, and Fan 2010), were provided to the students. Training for the environmental impact assessment tools such as SimaPro (Cavanagh et al., 2014b) and Sustainable Process Index (Narodoslawsky and Krotscheck, 1995) were also provided. Additionally, resources for enhanced technical writing and presentation skills were taught. These tutorials were scheduled appropriately as per the project's progress and requirements. Figure 1 highlights the resources and tools from PSE that our research lab (the Sustainable Design & Systems Medicine Lab) has access to at Rowan University.

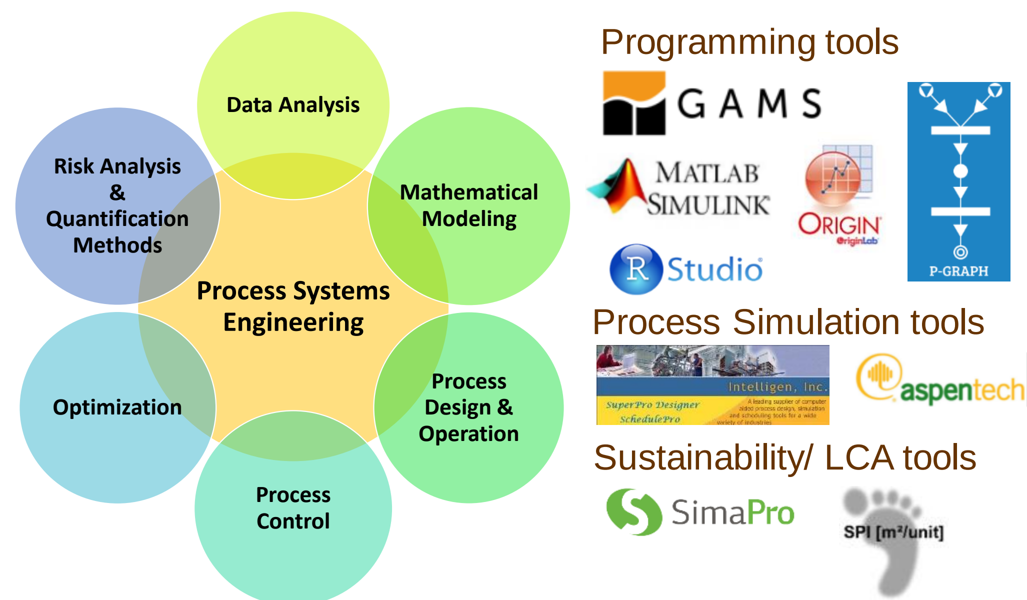

Figure 1: Process Systems Engineering (PSE) tools and computational resources at the Sustainable Design & Systems Medicine Laboratory at Rowan University.

2.3 Clinic Project; Solvent Recovery in Process Industries

This clinic project is funded by the US Environmental Protection Agency's Pollution Prevention Program. It addresses the two important national emphasis areas of (1) Business-based pollution prevention solutions supporting the Toxic Substances Control Act (TSCA) Priorities and (2) Hazardous materials source reduction approaches in States or Communities. The overall goal of this project is to develop a computational software tool that can help the chemical industry minimize solvent waste from chemical processes. The research strategy for the proposed project has been divided into the following specific aims:

Aim#1: Collect information and consult industries about solvent recovery issues in current practices

Aim#2: Create a list of potential solvent recovery technologies based on information collected about solvent applicability, toxicity, and physicochemical properties.

Aim#3: Develop technology models comprising of mathematical equations involving material and energy balances, utility (electricity, cooling water) requirements, equipment design, and costing

Aim#4: Based on properties of the solvent rich stream, devise a ranked list of the best recovery pathway which minimizes cost, reduces environmental impact, and limits the waste discharge

Aim#5: Develop a user-friendly computer-aided software program for the solvent recovery roadmap

An example case study from the pharmaceutical industry is analysed, and the results are explained in section#3.

3 Results

3.1 Economic Evaluation of IPA Recovery from Pharmaceutical Waste Stream

Pfizer and Rowan University had carried out an investigation with aims to recover and purify isopropanol (IPA) and minimize waste from the celecoxib process, which produces the API for an arthritis pain medicine known as Celebrex® (Slater et al., 2012). The waste stream following the final purification stage contains a significant amount of IPA. However, the results of laboratory-scale distillation and extraction conducted at the plant site failed to reach the purity requirement (Slater et al., 2012). The case study is a classic representation of an API purification process. In a batch process, the celecoxib process required 4,205 kg of IPA/batch. If incineration is selected as the waste solvent disposal method, then approximately 14.51 kg of steam and 0.83 kWh of electricity/kg IPA is required. Life cycle analysis (LCA) has determined that there is 2.19 kg of total emission/kg of IPA used within the process (Slater et al., 2012).

Azeotropic points are anticipated at 87.7 wt.% and 80.37°C, which means that separation solely through distillation will not be able to achieve the desired purity. A summary of IPA recovery model specifications is provided in Table 1, where we assumed a waste stream feed basis of 1000 kg/hr.

Table 1: Isopropyl Alcohol (IPA) recovery case study model specification for optimization

Feed Conditions	Feed Rates (kg/hr)	Outlet Requirements (%)
IPA 51%	510	Recovery: 99.5% IPA
Water 49%	490	Purity 99%

The general equations for process streams, costs, energy requirements, and theories concerning technologies are composed of linear and non-linear equations. The selection or non-selection is represented via binary variables in the superstructure. This example is formulated as a mixed-integer non-linear programming (MINLP) problem and solved in the GAMS programming language through Branch-and-

Reduce Optimization Navigator (BARON) algorithm. Although solvent recovery is inherently a multi-stakeholder problem, we concentrated our objective toward only cost minimization. The optimized path is presented in Figure 2, with an annualized cost of $524,000 (i.e., 14 cents/kg solvent recovered) over 25 years (Chea et al., 2020). This pathway was able to reach the desired output specification from Table 1 and presents a solution with the lowest potential cost in comparison to other alternative pathways. Figure 2B presents the cost distribution of the optimal pathway. The annualized capital cost accounts for up to 47% of the total costs of the optimal pathway, followed by other costs (overhead), membrane replacement, labor, and utility. The price of selecting this pathway may be reduced further if the pervaporation and ultrafiltration units are available onsite for retrofit.

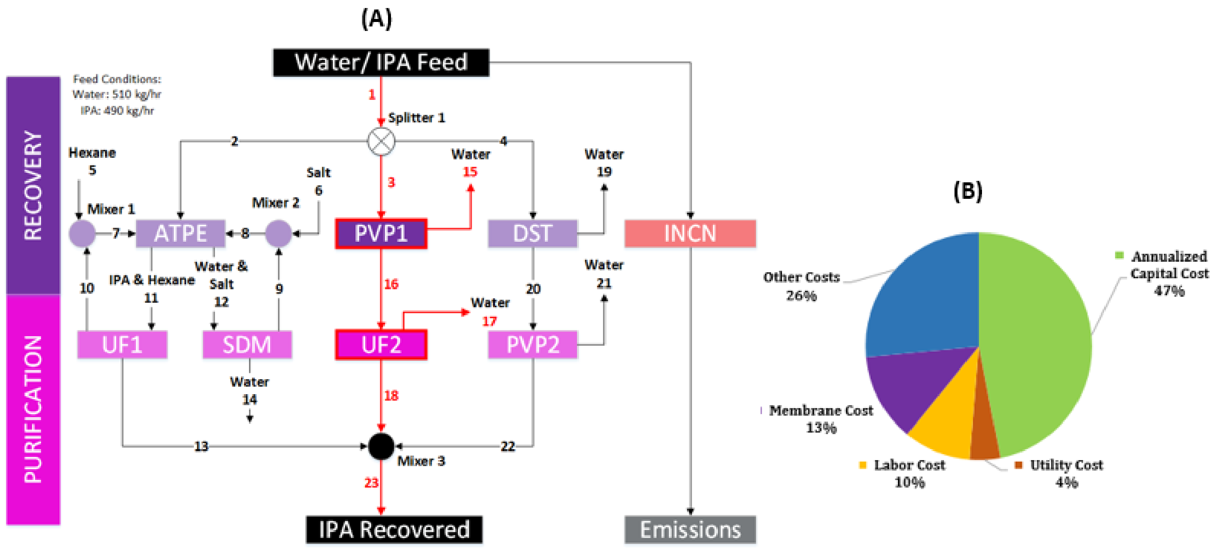

Figure 2: (A) A superstructure of the possible solvent recovery methods to separate IPA from the water. ATPE, UF, SDM, PVP, DST, and INCN represent aqueous two-phase extraction, ultrafiltration, sedimentation, pervaporation, distillation, and incineration, respectively. The most economically viable pathway for IPA recovery is highlighted in red. (B) The cost distribution of the optimal pathway (PVP1—UF2).

In comparison to incineration, solvent recovery is more economically viable. The cost required to incinerate the hypothetical waste flow rate of 1000 kg/hr requires $8.1 million/yr., which equates to $2.01/kg incinerated. The considerable increase in cost is attributed to the requirement for the heat of combustion. The organic solvent's chemical identity is irreversibly altered and thus cannot be reused within the process.

3.2 Environmental Impacts Assessment of IPA Recovery from Pharmaceutical Waste Stream

The environmental impacts of the optimized solvent recovery pathway were compared against conventional waste disposal methods. Sustainable process index (SPI) is an ecological footprint that measures the total arable area needed to embed a process into the ecosystem. SPI quantifies the environmental impacts of goods and services using material and energy flows. The primary assumption on which SPI is built on is that the natural source of environmental income to a sustainable economy is solar energy or radiation. Since the planet is finite, the area available to convert this income (solar radiation) into products and services is also finite. Therefore, the arable area needed to provide a service or goods is a convenient measure for the

SPI from an ecological sustainability point of view. Higher arable area needed to provide service goods corresponds to the increased impact on the ecosystem (Krotscheck and Narodoslawsky, 1996; Narodoslawsky, 2015; Narodoslawsky and Krotscheck, 1995, 2004). Human activities exert pressure on the ecosystem. To build up a process, humans depend on the ecosystem for resources such as both renewable and non-renewable energy, installation of equipment, and extraction of raw materials. Emissions are generated after the production of a product from a process. Therefore, an area in the ecosystem is needed to embed these air, water, and soil emissions aside from the areas needed for resource generation. The summation of these individual areas gives the total arable area needed to provide one unit of a product. Figure 3 shows the schematics for SPI.

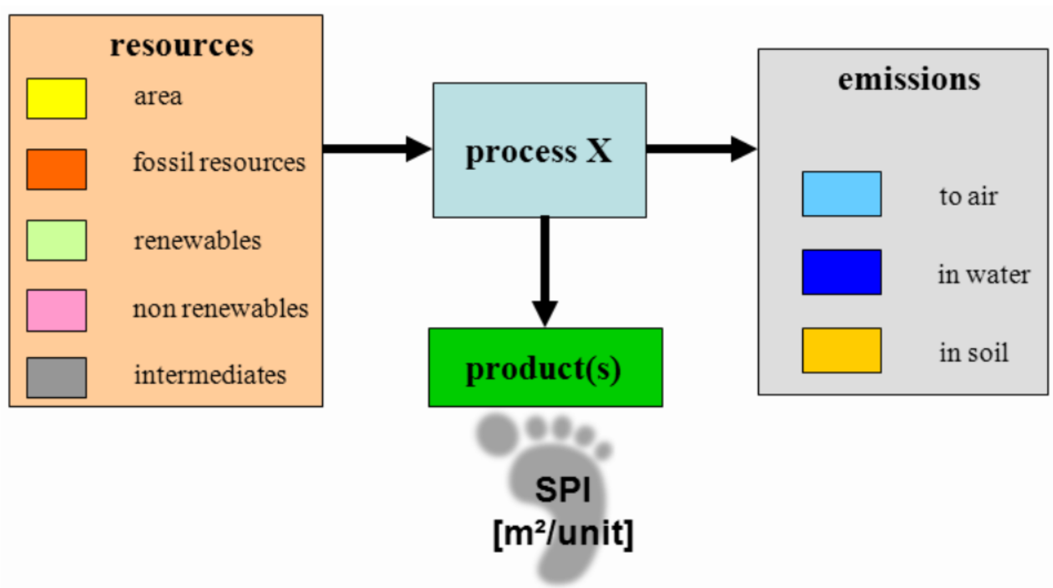

Figure 3. Schematics for sustainable process index. The resources are the inputs (quantified as arable area) to the process. Every process produces some emissions in the form of air, water, and soil. These emissions need to be embedded within an area in the ecosystem. The summation of these individual areas per unit of product(s) produced gives the SPI value.

The sustainability analysis for this case study was modelled using the sustainable process index footprint in SPIonWeb – an open-source software. For environmental impacts comparison, we considered three case scenarios, which include solvent recovery, direct disposal of the solvent waste into the environments, and incineration of the solvent waste. Table 2 shows the results for the case study from SPI analysis.

Table 2: Annual arable area (from SPI) needed to provide the services of direct disposal, solvent recovery, and incineration and the co$_2$ emissions and global warming potential associated with these services.

	SPI (m^2.a/unit)	**SPI (m^2.a/yr.)**	**CO_2 (kg/yr.)**	**Global Warming Potential (kg CO_2-eq/yr.)**
Direct Disposal	1988	8.03E+09	2.03E+07	2.17E+07
Solvent Recovery	128	4.93E+08	1.60E+06	1.69E+06
Incineration	405	3.21E+09	1.57E+07	1.71E+07

The total arable area needed for direct disposal and incineration supersedes that of solvent recovery by 93.9% and 84.6%, respectively. Thus, it will cost the ecosystem, an extra 93.9%, and 84.6% of natural income (arable area) if direct disposal and incineration were selected as the method of waste disposal. The annual CO_2 emission and global warming potential for both direct disposal and incineration supersede solvent recovery by 92.2% and 89.2%. Therefore, in all three scenarios, solvent recovery provides the best option for the treatment of hazardous waste.

Currently, we have completed the assessment of the economic and environmental impact separately, with greater emphasis on economics. If the cost of solvent recovery processes exceeds the price of common waste disposal methods significantly, then there is little incentive to choose recovery. Depending on the values of the company, more expensive recovery options may be chosen to minimize the overall environmental impacts. The next step in this work involves integrating this multi-objective complexity through the simultaneous modelling of both objectives using GAMS.

4 Summary

Through our unique engineering clinic program as well as synergistic efforts of the students, faculty, and staff at Rowan University, we were able to teach our students the importance of Sustainable Design in Chemical Engineering. In addition to project-based technical skills, the students also learned the importance of teamwork, technical writing, and presentation. Our students have presented this work at the AIChE (American Institute of Chemical Engineers) regional and national meetings, and in this process, they gained networking and communication skills. We believe that as engineering educators, it is our responsibility to teach the students the impact of systems-inspired design. Through all these activities, we were able to achieve our goals.

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